

An electrophysiological investigation of the temporal asynchrony effect on character-speech sound integration in Chinese typically developing children and children with dyslexia

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The data that support the findings of this study are available from the

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Research highlights

1. The present study found different neural correlates of character-speech sound integration in the temporal synchrony and temporal asynchrony conditions.
2. Congruency effects were observed on P1, N170 and N300 components when visual characters were presented synchronously with auditory speech sounds.
3. Congruency effects were observed on N200 component when auditory speech sounds were presented after visual characters by 300 or 600 ms.
4. Dyslexic children showed insufficient character-speech integration in the AV300 condition. Character-speech sound integration deficit in dyslexic readers was modulated by stimulus onset asynchrony.

Abstract

The neural mechanism of orthographic-phonological integration was influenced by the temporal relationship of cross-modal stimuli. However, previous studies mainly investigated the neural mechanism of letter-speech sound integration in precise temporal synchrony or small temporal asynchrony conditions. In this study, character-speech sound integration was investigated in a relatively wide temporal window. Chinese characters were presented synchronously to the onset of speech sounds or before speech sound by 300 or 600 ms (referred as AV0, AV300 and AV600). ERP responses evoked by congruent condition (speech sounds were paired with congruent visual characters) and baseline condition (speech sounds were paired with Korean characters) were compared. Different electrophysiological markers were found in the temporal synchrony and temporal asynchrony conditions. In the AV0 condition, developing dyslexia (DD) and typically developing (TD) children showed similar congruency effect on P1, N170 and N300 components, demonstrating the influence of speech sound on visual character processing. In the AV300 condition, DD group showed left-lateralized congruency effect on N200, whereas TD children showed bilateral congruency effect on N200. Both groups showed bilateral congruency effect on N200 in the AV600 condition. We speculate that the insufficient character-speech sound integration exhibited by dyslexic children in the AV300 condition was probably caused by their slow visual processing speed. The results provide unique insight into the neural mechanism of print-speech integration in a wide temporal window and point out the necessity to investigate neural mechanism of print-speech integration in a relatively wide temporal window.

Keywords: orthographic-phonological integration, multisensory, temporal

asynchrony, event-related potentials (ERP), neural correlates, developmental dyslexia

1. Introduction

Reading is essential to children's academic achievement, and is associated with future social and economic success in the literate culture. Although most people acquire literacy skills easily, around 5-10% of children are affected by developmental dyslexia and suffer from different degrees of reading difficulties (Lyon, Shaywitz, & Shaywitz, 2003). Developmental dyslexia (DD) is a learning disorder characterized by difficulties in accurately and/or fluently reading in spite of an average IQ, adequate schooling, and normal sensory acuity (Lyon, Shaywitz, & Shaywitz, 2003). The acquisition of grapheme-phoneme associations is one of the basic requirements for fluent reading and its failure may contribute to reading difficulties in developmental dyslexia (Žari

et al., 2014; Wimmer & Schurz, 2010; Blomert, 2011; Wallace & Stevenson, 2014; Hahn, Foxe, & Molholm, 2014). Many dyslexia interventions contain a condition focused on letter-speech sound mapping training (Aravena, Snellings, Tijms, & van der Molen, 2013; Tijms & Hoeks, 2010). However, the nature and mechanisms involved in orthographic-phonological integration are still unclear (Mercier & Cappe, 2020).

One critical factor affecting the success of audiovisual integration is temporal proximity (Calvert, Spence, & Stein, 2004). In an fMRI study, van Atteveldt, Formisano, Blomert and Goebel (2007) investigated the effect of temporal asynchrony on letter-speech sound integration. In their study, a heteromodal area in superior temporal sulcus (STS) and a modality-specific auditory association cortex were identified to be involved in letter-speech sound integration. The STS receives visual information and auditory information. Visual letters influenced the processing of speech sounds by sending feedback from STS to the auditory association cortex

(van Atteveldt, Formisano, Blomert & Goebel, 2007). Most interestingly, integration (stronger BOLD response to congruent letter-sound pairs than to incongruent letter-sound pairs) in the left STS occurred within a relatively wide temporal window (about 300 ms), whereas integration in auditory association areas depended on temporal synchrony. The findings provided evidence for the influence of temporal asynchrony on letter-speech sound integration.

Although fMRI studies provide insight about precise localization of the neural mechanisms involved in letter-speech sound integration, they cannot provide precise temporal information of the processing. Precise neural time course of letter-speech sound integration can only be investigated with a high temporal resolution method such as event-related potentials (ERP). To date, only a few studies have investigated the effect of temporal asynchrony on letter-speech sound integration using ERP technique. Most of the studies used the mismatch negativity (MMN) as an index of automatic letter-speech integration. The MMN is evoked between 100 and 200 ms after stimulus onset and is considered to reflect the neurophysiological correlate of a comparison process between an incoming deviant auditory stimulus and the memory trace of repeatedly presented standard auditory stimulus (Schröger, 1998).

Froyen, Van Atteveldt, Bonte and Blomert (2008) recorded EEG data while healthy Dutch adult readers completed a passive oddball task in which speech sounds (standard, 90%; deviant, 10%), letter/speech sound pairs (the visually presented letter was always an “a”, irrespective of the speech sound) were presented. The stimulus onset asynchronies (SOAs) between the presentation of the letter and speech sound were manipulated, including synchronous condition (AV0) and two visual-leading auditory conditions (100 or 200 ms, referred to as AV100 or AV200 from here on). Compared with the MMN in isolated auditory condition, larger MMN amplitude

(reflecting integration) in audiovisual condition was only found in the AV0 condition. Likewise, Mittag and colleagues (2011, 2013) found enhanced MMN amplitude in healthy adult readers in the AV0 condition but not in the AV200 condition. The results in children were slightly different. When investigated SOA effects on letter-speech sound integration in typically developing (TD) children, Froyen, Bonte, Van Attevelde and Blomert (2009) did not find enhanced MMN amplitude in the AV0 condition, but found enhanced MMN amplitude in the AV200 condition. The authors explained the MMN as reflecting a mature and automatic cross-modal integration. The absence of enhanced MMN in the AV0 condition indicated that automatic print-speech integration has not been fully developed in the children. Employing an adapted version of the oddball paradigm of Froyen and colleagues (2008, 2009, 2011), Žarić and colleagues (2014) examined SOA effects on letter-speech sound integration in three groups of children (typical readers, dysfluent dyslexics, and severe dysfluent dyslexics). In the AV0 condition, enhanced MMN amplitudes were observed both in typical readers and in dysfluent dyslexics. In the AV200 condition, enhanced MMN amplitudes were found in all groups. The authors attributed the different findings between their study and studies by Froyen and colleagues (2009, 2011) to the methodological differences such as proportion of deviants (increased from 10% or 15% to 17%) and trial length (increased from 1250 ms to 1700 ms) (Žarić et al., 2014).

Taken together, the aforementioned studies reveal interactions between temporal proximity and experimental parameters in the MMN integration effect, indicating that temporal synchrony or small temporal asynchrony is critical for the integration effect reflected by MMN. According to brain imaging studies, the major MMN source is located in the early auditory cortex (Alho, 1995; Giard, Perrin, Pernier & Bouchet,

2010), including the auditory association cortex which is reported to be dependent on temporal synchrony (van Atteveldt, Formisano, Blomert & Goebel, 2007). The dependence of temporal synchrony in MMN integration effects observed in the ERP studies resembles that in the auditory association cortex observed in the fMRI study by van Atteveldt, Formisano, Blomert and Goebel (2007). In that case, it is reasonable to speculate that MMN is not suitable for investigating the neural mechanism of multisensory integration at a relatively wide temporal window. However, letter-speech sound integration can occur at relatively long temporal asynchronies (Nash et al, 2016; Clayton & Hulme, 2017; Hasko, Bruder, Bartling & Schulte-Körne, 2012). It is necessary to describe a whole temporal profile for the neural mechanisms of letter-speech integration using other electrophysiological markers. Moreover, letter-speech integration includes multiple processing stages. In the fMRI study by van Atteveldt, Formisano, Blomert and Goebel (2007) and the ERP studies by Froyen and colleagues (2008, 2009, 2011), the neural correlates of integration only reflected the influence of visual letter on speech processing. The influence of speech sound on visual stimuli was not illustrated. In the study by Froyen, van Atteveldt and Blomert (2010), visual MMN was used to investigate the influence of speech sound on letter processing but no visual MMN amplitude modulation was found. Exploring letter-speech sound integration with other electrophysiological signatures provides an opportunity to reveal both sides of letter-speech sound integration.

Under these circumstances, the first aim of the current study was to explore the neural mechanisms of print-speech integration across a wide range of temporal asynchrony using electrophysiological correlates that are less dependent on temporal synchrony. Compared with typical readers, dyslexic readers have been reported to show broader temporal integration window for both speech and non-speech stimuli

(Laasonen, Service, & Virsu, 2002; Virsu, Lahti-Nuuttila, & Laasonen, 2003; Hairston et al., 2005; Wallace & Stevenson, 2014; Meilleur, Foster, Coll, Brambati, & Hyde, 2020). The second aim of this study was to examine whether dyslexic children exhibit different neural mechanisms of letter-speech sound integration from typically developing children. To this end, Chinese dyslexic children and nondyslexic children were recruited as participants. In the present study, three levels of SOA were included: synchronous condition (AV0), visual leading auditory stimuli by 300 ms (AV300), and visual leading auditory stimuli by 600 ms (AV600). We chose 0 and 300 ms SOA since these SOAs have been proved to be effective and used in the study by van Atteveldt, Formisano, Blomert and Goebel (2007). We chose the 600 ms SOA because it is close to the 500 ms SOA used in the study by Clayton and Hulme (2017) and is shorter than the 1000 ms SOA used in the study by Nash et al. (2016). High temporal resolution event-related potentials (ERPs) were used to measure the real time print-speech integration processing in all SOA conditions. ERP waveforms induced by the onset of auditory stimuli were analyzed.

2. Method

2.1. Participants

Thirty children between the ages of 9 and 11 were recruited from primary schools in Beijing. The children were in grade 3 to 6. There were 14 children with developing dyslexia (DD: 4 females and 10 males, mean age was 10.10 years) and 16 typically developing children as controls (TD: 5 females and 11 males, mean age was 10.29 years). All participants were right-handed with Chinese as their native language, had normal or corrected-to-normal vision, and did not report a history of neurological or psychiatric disorders. Two participants in the control group and one in the dyslexic

group were excluded in the following ERP analysis because of the excessive artifacts. This study was approved by the Ethics Committee of the Institute of Psychology, Chinese Academy of Science. Prior to the experiment, written informed consent was obtained from the guardians of the children.

The inclusion criteria for selecting children with dyslexia were adopted from the studies conducted with Mandarin-speaking Chinese participants (Meng, Cheng-Lai, Zeng, Stein, & Zhou, 2011; Wang, Bi, Gao, & Wydell, 2010). Intelligence quotient (IQ) and vocabulary size were assessed by Combined Raven's Progressive Matrices Test (CRT) (Li, Chen, & Jin, 1989) and Chinese Character Recognition Test (CCRT) (Wang & Tao, 1996), respectively. In Combined Raven's Test, nonverbal intelligence was tested by a series of matrices with increasing difficulty. In Chinese Character Recognition Test, 210 characters are divided into 10 sub-groups according to levels of difficulty. The participants were required to write down a compound word using a given Chinese character. For example, if they see the character 草 (*grass*), they should write down a compound word such as 草地 (*grassland*), 草坪 (*grass-plot*), ect. The raw score for each sub-group multiplied a coefficient corresponding to the difficulty level, and then the scores for the ten sub-groups were summed up for each participant. Those individuals with normal IQ ($IQ > 85$) and low score in CCRT (at least one and a half standard deviations below the average score of typically developing children in the same grade) were recruited as dyslexic participants in this study.

2.2. Reading-related Measures

Prior to the ERP experiment, both groups of children participated in a series of linguistic-cognitive tests, including reading fluency, reading accuracy, morphological awareness, phonological awareness, rapid naming, short-term memory, and visual spatial attention. The detailed information of the participants is presented in Table 1.

Reading fluency test

This test was developed by Qian, Deng, Zhao, and Bi (2015) which includes a fixed list of 160 high frequency (233.71 occurrence per million) Chinese characters that were selected from the Modern Chinese Frequency Dictionary (1986). The children were required to read aloud each character as fluently and accurately as they can within 1 min. The number of correctly read words was recorded to represent their reading fluency score.

Reading accuracy test

A list of 172 characters with increasing difficulty (i.e., increasing stroke numbers and decreasing word frequency) was presented on a paper. Participants were asked to read each character aloud in sequence. When the participant failed to correctly read five characters consecutively, the test was terminated. Participants were scored on the total number of correctly read characters.

Morphological awareness test

A morpheme judgment task similar to that in Shu, McBride-Chang, Wu, and Liu (2006) was used in this study. The test contains 20 pairs of two-character Chinese words. Each pair of words shared one character (e.g., 等级 vs. 等待, meaning *level* vs. *wait*). Participants were asked to judge whether the identical characters in the pairs had the same meaning, i.e., whether the identical characters represent the same morpheme or not. One point was scored for each correct judgment.

Phonological awareness task

Phonological awareness was measured by an oddball paradigm adopted from Qian and Bi (2015). There were three subtests corresponding to three types of oddity, which were onset, rime and lexical tone respectively. There were ten trials for each type of oddity. In each trial, three Chinese characters were presented orally by the

experimenter. Participants were required to identify the phonologically odd item among them. One point was scored for each correct judgment.

Rapid automatized naming task (RAN)

This task was adapted from Denckla and Rudel (1976). RAN was measured by two subtests including picture naming and digit naming. Five pictures (e.g., flower, book, dog, hand, shoe) or five digits (e.g., 2, 4, 6, 7, 9) were presented repeatedly in random order in a six row×five column grid. The children were instructed to name each picture or digit in sequence as quickly as possible. All items were read twice. Naming latencies were recorded with a stopwatch and the final score was the average time of the two readings. The higher score means the slower speed of naming.

Short-term memory task

The WAIS- III (Wechsler Adults Intelligence Scale version III, Wechsler, 1997) subtest was used. The test has two parts: forward memory and backward memory. In forward memory subtest, the children were presented with a list of numbers and then asked to repeat them sequentially. In backward memory subtest, the children were presented with a list of numbers and required to repeat the numbers in reverse order. The number of test items increases gradually. When the children made two consecutive mistakes, the test will stop. The largest correct number was taken as the final score.

Visual spatial attention

A digit cancellation task was used to test the visual spatial attention (see Takeshi, Kazuhito, Yasuhiro, Mitsuhito, & Hidehiro, 2013). Numbers from 0 to 9 were repeatedly presented in a 25 rows × 40 columns matrix. Participants were instructed to search through the matrix and deleted the number “3” sequentially in three minutes. The visual spatial attention ability is measured as ‘correct number – (false number +

0.5 × missed number)’. The higher score means the better visual spatial attention ability.

2.3. Stimuli and Procedure

A passive priming task adapted from the study by Nash and colleagues (2016) was employed in this experiment. There were six experimental conditions: bimodal congruent at 3 SOAs (AV0, AV300, and AV600) and bimodal baseline at 3 SOAs. In the congruent condition, the prime was a visually presented Chinese single character and the target was the corresponding speech sound. In the baseline condition, the prime was a visually presented Korean character and the target was a Chinese speech sound. Speech sounds were recorded by a female native Chinese speaker and digitally converted to 16-bit resolution at a sampling rate of 44.1 kHz. The mean duration of speech sound was 426.04 ms (SD=111.13). Visual stimuli consist of 80 Chinese single characters and 80 stroke-matched Korean characters. Korean characters were used for non-word symbols as they are unfamiliar to the children in this study.

The priming task was run using E-prime version 2.0 (Schneider, et al. 2002). A schematic description of stimuli presentation is shown in Figure 1. At the beginning of each trial, a central fixation was presented for 500 ms. Next a black visual character appeared on a white screen for 1000 ms. The characters were written in Song font size 72. They were presented on a 17 inch screen and the children sat 70 cm from the screen. The auditory stimuli were presented over headphones simultaneously with the visual characters or after a 300 ms or 600 ms time delay. A blank screen with a random interval from 500 to 1000 ms was presented after the offset of the visual characters. Participants were instructed to look at the characters and listen to the sounds. Catch trials were included to ensure that the children were attending to the stimuli during the task. In the catch trial, children were required to press the spacebar

when they saw a yellow cartoon picture. There are 5 blocks in the formal experiment, each block contains 96 experimental trials and 16 catch trials. There are 560 trials in total. The duration of formal experiment is about 30 min (break time was not included). Before formal experiment started, a practice session including 20 trials was presented to the children to familiarize with the experimental procedure.

2.4. EEG recording and ERP analysis

Using 64-channel electrode cap (NeuroScan II Inc., El Paso, TX, USA), EEG data were collected in a quiet and dimly-light room. Electrodes were positioned according to the Extended International 10-20 System. The channels were referenced to left mastoid. In addition, four bipolar electrodes were used to record vertical and horizontal eye blinks. EEG data were sampled at 1000Hz and bandpass filtered from 0.05 Hz to 100 Hz online. Electrode impedance levels were kept below 5 k Ω .

The raw data were processed offline using EEGLAB (Delorme and Makeig, 2003; <http://www.sccn.ucsd.edu/eeglab>). Data were re-referenced to the average of the 64 electrodes and bandpass filtered from 0.1 Hz to 40 Hz. An independent component analysis (ICA) was run on the pre-processed data in order to reduce artifacts caused by eye movement or body motion. Then the EEG data were segmented into epochs that began from 100 ms before the onset of the auditory stimuli and ended 700 ms after the onset of the auditory stimuli. The 100 ms interval before stimuli onset was used as baseline. Epochs were rejected if amplitudes exceeded $\pm 100 \mu\text{V}$. The mean number of accepted epochs for each condition and group are illustrated in Table 2. Epochs were averaged for each condition and each group. Catch trials were not analyzed. The layout for configuration of electrodes and selection of electrodes for data analysis were shown in Figure 2. Mixed-design ANOVAs with Greenhouse–

Geisser correction were applied to analyze the ERP data. The alpha level for all analyses was 0.05.

3. Results

3.1 Synchronous audiovisual condition (AV0)

Grand-average ERPs in response to the simultaneous onset of visual and auditory stimuli for all conditions and groups are plotted in Figure 3 for representative electrodes. The occipito-temporal P1, N170, and fronto-temporal N300 were observed in the AV0 condition.

P1

Peak latency was measured in the time window of 100-180 ms and averaged amplitude was measured in a 40 ms time window centered on the peak latency. Mixed-design ANOVAs with Greenhouse-Geisser correction were performed on the latency and amplitude of P1, with group as between-subject factor, and trial type (congruent, baseline), laterality (left hemisphere: P7, PO7, PO5, and right hemisphere: P8, PO8, PO6) as within-subject factors. For the P1 latency, the interaction between trial type and laterality was significant ($F(1,25) = 7.36, p = .012, \eta^2 = .227$). P1 latency was marginally longer in congruent condition in comparison to baseline condition on the left hemisphere (141 vs. 134 ms, $t(26) = 2.01, p = .055$). No difference was found in the P1 latencies between the two conditions on the right hemisphere (138 vs. 139 ms, $t(26) = -0.496, p = .624$). No significant effect was found for the P1 amplitude.

N170

The N170 peak latency was measured in the time window of 180-250 ms, mean N170 amplitude was measured by the average of a 40 ms time window centered on the peak latency. Mixed-design ANOVAs with Greenhouse-Geisser correction were performed on the latency and amplitude of N170, with group as between-subject factor, and trial type (congruent, baseline), laterality (left hemisphere: P7, PO7, PO5, and right hemisphere: P8, PO8, PO6) as within-subject factors. Significant main effect of trial type was found for N170 latency, ($F(1,25) = 6.22, p = .02, \eta^2 = .199$). In comparison to baseline condition, congruent condition induced longer N170 latency (212 vs. 206 ms, $t(26) = 2.51, p = .019$). For the N170 amplitude, the main effect of trial type is significant ($F(1,25) = 8.06, p = .009, \eta^2 = .244$). When compared with baseline, congruent trials evoked larger N170 amplitude (-2.54 vs. -1.28 μ V). The main effect of laterality is marginally significant ($F(1,25) = 4.14, p = .053, \eta^2 = .142$), with greater N170 amplitude on the left hemisphere (-2.88 vs. -0.93 μ V). The main effect of group is significant ($F(1,25) = 6.52, p = .017, \eta^2 = .207$), with larger N170 amplitude in the TD group (-3.67 vs. -0.15 μ V). No significant interaction was found for N170.

N300

N300 was broadly distributed in the fronto-temporal area in the AV0 condition. The mean amplitude of N300 was measured in a 260-340 ms time window. Mixed-design ANOVAs with Greenhouse-Geisser correction were performed on the average N300 amplitude, with group as between-subject factor, and trial type (congruent, baseline), laterality (left hemisphere: F7, F5, F3, midline: FP1/2, FPZ, AF3/4, F1/2, FZ, and right hemisphere: F8, F6, F4) as within-subject factors. The main effect of trial type is significant ($F(1,25) = 27.28, p < .001, \eta^2 = .522$), with larger N300 amplitude in the baseline condition (-4.55 vs. -6.83 μ V). The main effect of laterality

is significant ($F(2, 50) = 3.63, p = .034, \eta^2 = .127$). In comparison to the right hemisphere, the N300 amplitude was larger on the midline (-6.04 vs. $-4.9 \mu\text{V}$, $t(26) = 2.3, p = .03$). No other significant main effect or interaction was significant.

3.2 AV300 condition

Grand-average ERPs in response to the onset of auditory stimuli for all conditions and groups are plotted in Figure 4 for representative electrodes. A fronto-temporal negativity peaked around 200 ms was found in the AV300 condition. The mean N200 amplitude was measured in a 170-230 ms time window. Mixed-design ANOVAs with Greenhouse-Geisser correction were performed on the average N200 amplitude, with group as between-subject factor, and trial type (congruent, baseline), laterality (left hemisphere: F7, F5, FT7, FC5, midline: AF3, FP1, FP2, FPZ, AF4, and right hemisphere: F6, F8, FC6, FT8) as within-subject factors. The main effect of trial type was significant ($F(1,24) = 19.78, p < .001, \eta^2 = .452$), with greater amplitude in the congruent condition (-6.83 vs. $-4.55 \mu\text{V}$). The main effect of laterality was significant ($F(2, 48) = 18.19, p < .001, \eta^2 = .431$), with largest amplitude on the midline ($ps < .001$). There is no difference between the amplitudes on the left hemisphere and right hemisphere. The interaction of trial type, laterality and group was significant ($F(2, 48) = 3.29, p = .046, \eta^2 = .121$). Follow-up ANOVAs showed significant group effect ($F(1,24) = 4.29, p = .049, \eta^2 = .151$) and interaction between trial type and group ($F(1,24) = 4.77, p = .039, \eta^2 = .166$) on the right hemisphere. In comparison to the DD group, the TD group showed larger N200 amplitude on the right hemisphere (-2.65 vs. $-0.52 \mu\text{V}$). Furthermore, for the TD group, congruent trials evoked larger N200 amplitude as compared with baseline on the right hemisphere (-3.50 vs. $-1.80 \mu\text{V}$, $t(12) = -3.69, p = .003$). But no difference was found in the amplitudes between the two conditions for DD group.

3.3 AV600 condition

Grand-average ERPs in response to the onset of auditory stimuli for all conditions are plotted in Figure 5 for representative electrodes. Similar as in the AV300 condition, a fronto-temporal N200 was found in the AV600 condition. Mean amplitude of N200 was measured in a 150-250 ms time window. Mixed-design ANOVAs with Greenhouse-Geisser correction were performed on the average amplitude, with group as between-subject factor, and trial type (congruent, baseline), laterality (left hemisphere: F7, F5, FT7, FC5, and right hemisphere: F6, F8, FC6, FT8) as within-subject factors. The main effect of trial type was significant ($F(1,24) = 9.02, p = .006, \eta^2 = .273$). In comparison to baseline, congruent condition evoked larger N200 amplitude (-1.25 vs. -0.12 μV). The main effect of group was significant ($F(1,24) = 5.52, p = .027, \eta^2 = .25$), with larger amplitude in the TD group (-1.52 vs. 0.14 μV). No other significant effect was found.

3.4 Relationships between the measures of integration effect and reading-related skills

To further investigate whether the congruency effects (differences between ERP amplitudes in the congruent and baseline conditions) correlate with individual reading-related skills, we calculated partial correlation coefficients (controlling for age, IQ, and vocabulary size) between congruency effect and scores of reading skills in the total population (both groups, adopting two-tailed significance level of $\alpha = 0.05$) and in each group (adopting two-tailed significance level of $\alpha = 0.05$) separately. Since the present study focuses on the SOA effect on audiovisual integration in different groups, we present analyses separately for the TD and DD groups.

In the AV0 condition, different correlations were found in the two groups. In the TD group, the congruency effect on P1 amplitude was strongly correlated with reading fluency ($r = .67, p = .012$) and RAN ($r = -.66, p = .011$) on the right hemisphere. The congruency effect on P1 latency was significantly correlated with reading accuracy ($r = .613, p = .044$) on the right hemisphere. For the congruency effects on P1 amplitude or latency, positive values reflected greater congruency effects. The correlation coefficient between congruency effect on P1 amplitude and reading fluency, between congruency effect on P1 latency and reading accuracy were positive, indicating that a larger congruency effect was associated with higher reading fluency and reading accuracy. The correlation coefficient between congruency effect on P1 amplitude and RAN was negative, indicating that a larger congruency effect was associated with higher naming speed (smaller scores in RAN test). The correlation between the congruency effect on N300 amplitude and visual spatial attention was significant on the right hemisphere ($r = .613, p = .044$). For the congruency effects on N300 amplitude, positive values reflected greater congruency effects. The positive correlation coefficient means that a larger congruency effect was associated with higher visual spatial attention capacity. In the DD group, significant correlation was found between the congruency effect on P1 latency and morphological awareness ($r = .662, p = .037$) on the right hemisphere, suggesting that greater congruency effect was associated with better morphological awareness. A significant correlation was found between the congruency effect on N300 amplitude and RAN ($r = .707, p = .022$) on the right hemisphere. Since larger scores in RAN test means lower naming speed, the positive correlation coefficient between congruency effect on N300 amplitude and RAN reflecting that greater congruency effect was associated with slower naming speed.

In the AV300 condition, the correlation between the congruency effect on N200 amplitude and RAN was strong and significant ($r = .686, p = .028$) on the left hemisphere. For the congruency effects on N200 amplitude, negative values reflected greater congruency effects. The positive correlation coefficient between congruency effect on N200 amplitude and rapid naming means that the greater congruency effect was associated with higher naming speed. In the DD group, the correlation between the congruency effect on N200 amplitude and visual spatial attention was significant ($r = -.65, p = .042$) on the left hemisphere. The negative correlation coefficient between congruency effect on N200 amplitude and visual spatial attention in the DD group means that the greater congruency effect was associated with higher visual spatial attention capacity. No significant correlation was found between the congruency effect on N200 amplitude and reading-related skills for both groups in the AV600 condition.

4. Discussion

The current study investigated electrophysiological correlates of cross-modal character-speech sound processing in developmental dyslexia and typically developing children in different SOA conditions. Different neural correlates were found in the temporal synchrony and temporal asynchrony conditions. Congruency effects were found for both groups across all the three SOAs. Difference in congruency effects between the DD and TD children was only found on the right hemisphere in the AV300 condition, where TD children exhibited significant congruency effect and children with dyslexia did not. The main findings are discussed in turn below.

4.1 Electrophysiological indices of congruency effects in the AV0 condition

In the AV0 condition, the concurrently presented stimuli induced P1 and N170 components in the occipito-temporal area and N300 in the fronto-temporal area. Congruent trials induced longer P1 latency, longer N170 latency and larger N170 amplitude in comparison to baseline. The P1 component has been linked with physical characteristic of stimuli and selective attention (Hillyard, Teder-Sälejärvi & Münte, 1998). The N170 was associated with the activity of visual word form area and was sensitive to orthographic information (Cohen et al., 2000; Sehyr, Midgley, Holcomb, Emmorey, & Behrmann, 2020). The increased latencies of P1 and N170 have been linked to a delay in visual processing speed (Bieniek, Frei, & Rousselet, 2013), suggesting that the large sensory processing load in the early stage of audiovisual integration will slow down the visual processing speed. We speculated that the greater N170 amplitude indicates increased cognitive processing load and more orthographic processing effort. As P1 and N170 reflect early processing of visual stimuli, the observed congruency effects on P1 and N170 reflect the influence of speech sound on visual character processing, but not the influence of visual character on speech sound processing.

A fronto-temporal N300 congruency effect was found in a later stage, with congruent trials inducing smaller N300 amplitude in comparison to baseline. The latency and distribution of N300 resemble previously reported N300 in tasks requiring access to phonological representations of visual words (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Spironelli & Angrilli, 2007). In children, N300 was found to be associated with the integration of orthographic and phonological representations over the fronto-temporal lobe (Penolazzi, Spironelli, Vio, & Angrilli, 2006). Lower N300 amplitude in congruent condition was thought to reflect successful perceptual integration or the access of mental representation (Male &

Gouldthorp, 2020), which was consistent with the finding on N300 congruency effect in this study. In the study by Hasko, Bruder, Bartling and Schulte-Körne (2012), auditory stimuli were presented before visual word, left-lateralized word-speech integration on N300 was found in TD children and bilateral word-speech integration on N300 was found in DD group. Such left-lateralized N300 congruency effect was not found in the present study, probably because visual characters and speech sounds were presented synchronously in the AV0 condition. The difference demonstrates the important influence of temporal asynchrony on the neural mechanism of print-speech sound integration.

4.2 Electrophysiological indices of congruency effects in the AV300 and AV600 conditions

In the AV300 and AV600 conditions, auditory speech sounds induced a fronto-temporal N200 component. In both conditions, congruent trials induced larger N200 amplitudes in comparison to baseline. The N200 component has been related to several functional mechanisms, such as working memory processes (Sams, 1983), the acquisition of implicit knowledge (Tatiana et al., 2014), selective pre-attentive stimulus evaluation and stimulus discrimination (Howe, 2014; Polich, 2007). In children, fronto-central N200 responses induced by auditory stimulus are thought to represent encoding of acoustic properties in both primary and secondary auditory cortices (Ponton, Eggermont, Kwong, & Don, 2000). We tentatively speculate that the N200 component may reflect online encoding of acoustic information since it was induced by the onset of auditory speech sound.

In the AV300 condition, dyslexic children revealed congruency effect over left fronto-temporal electrode sites, whereas TD group revealed bilaterally distributed congruency effect. This difference may be caused by the well-documented visual

perceptual difficulties (Cornelissen, Hansen, Hutton, Evangelinou, & Stein, 1998; Livingstone, Rosen, Drislane, & Galaburda, 1991) or auditory perceptual difficulties (Helenius, Uutela, & Hari, 1999) in dyslexic readers. Numerous studies have indicated that dyslexics exhibited a visual processing difficulty, particularly in rapid visual temporal processing (Lovegrove, Slaghuis, Bowling, Nelson, & Geeves, 1986). Specifically, dyslexic readers exhibited an asymmetric sluggish attention capture in the left visual field (Facoetti & Molteni, 2001; Jaśkowski & Rusiak, 2008), which may result in insufficient visual processing of character on the right hemisphere. The insufficient character processing in turn contributed to the absence of N200 congruency effect on the right hemisphere in DD group. Another possible reason for the absence of N200 congruency effect on the right hemisphere in dyslexic children may be their asymmetrical deficit in auditory processing. Previous data have shown reduced phase entrainment by the dyslexic participants in right hemisphere auditory networks (Cutini, Szűcs, Mead, Huss, & Goswami, 2016), and impaired neuro-electric oscillations in Theta and Delta band on the right hemisphere (Goswami, 2011). Such deficits may explain the weak N200 response on the right hemisphere in dyslexic children.

Multisensory integration starts from the cross-modal inputs to sensory cortices (Cappe, Thut, Romei, & Murray, 2010; Mercier & Cappe, 2020). As each sensory system has its own processing speed (Breznitz, 2006), the gap between visual processing speed and auditory processing speed may affect the quality of integration (Shaul, 2014). In the AV600 condition, the temporal disparity between visual characters and speech sounds was relatively long, allowing the dyslexic children to process visual characters more sufficiently, thus leading to equivalent N200 congruency effects on both hemispheres. In the AV300 and AV600 conditions, the

congruency effects on N200 reflect the influence of visual characters on the processing of speech sounds. In the AV300 and AV600 conditions, different findings on the laterality of N200 congruency effect were found in dyslexic children, demonstrating the important influence of visual information on speech sound processing.

4.3 Relationships between the neural correlates of congruency effects and reading skills

The relationships between neural correlates of congruency effects and behavioral measures of reading-related skills were different in the two groups. In the AV0 and AV300 conditions, reading-related skills correlated with the congruency effects in expected direction in TD children, with better readers showing greater congruency effects. In the AV0 condition, RAN correlated with N300 congruency effect in the opposite direction in dyslexic children, suggesting the greatest congruency effect for the poorest readers. The TD children revealed significant correlation between visual spatial attention and congruency in the AV0 condition, whereas dyslexic children revealed significant correlation between visual spatial attention and congruency effect in the AV300 condition. The slow involvement of visual spatial attention may confirm a deficit in attention capture in dyslexic children (Facoetti & Molteni, 2001; Jaśkowski & Rusiak, 2008). No significant correlation between reading-related skills and congruency effect was found in the AV600 condition, suggesting that the influence of reading-related skills on neural congruency effects depends on the temporal relationship between cross-modal stimuli. In general, the neural correlates of congruency effects can index reading-related skills in TD children. But the relationships between reading-related skills and the neural correlates of congruency effect in dyslexic children were more complicated.

4.4 Limitations of the present study

Lastly, it is important to point out possible limitations of our study. One limitation is the small sample size of the subgroups. In future, the study should be repeated with a larger sample size in order to gain power and to assess whether the results are replicable and powerful. The second limitation is that only the influence of speech sounds on processing of visual characters was observed in the AV0 condition. The ERP responses may be visual-dominant in the passive viewing and listening task, future study should employ an active task to direct participant's attention to the speech sounds.

Conclusion

The present study found different neural correlates of character-speech sound integration in the temporal synchrony and temporal asynchrony conditions. Congruency effects on P1, N170 and N300 reflect the influence of speech sound on visual character processing in the AV0 condition. Congruency effects on N200 in the AV300 and AV600 conditions reflect the influence of visual character on speech sound processing. Compared with TD children, dyslexic children showed insufficient character-speech integration in the AV300 condition, suggesting that character-speech sound integration deficit in dyslexic readers was modulated by the temporal relationships between visual and auditory stimuli.

References

- Alho, K. (1995). Cerebral Generators of Mismatch Negativity (MMN) and Its Magnetic Counterpart (MMNm) Elicited by Sound Changes. *Ear and Hearing*, 16(1), 38-51.
- Aravena, S., Snellings, P., Tijms, J., & van der Molen, M.W. (2013) A lab-controlled simulation of a letter–speech sound binding deficit in dyslexia. *Journal of Experimental Child Psychology* 115(4), 691–707.
- Arnaud, D., & Scott, M. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J Neurosci Methods*, 134(1), 9-21.
- Bentin, S., Mouchetant-Rostaing, Y., Giard, M. H., Echallier, J. F., & Pernier, J. (1999). ERP Manifestations of Processing Printed Words at Different Psycholinguistic Levels: Time Course and Scalp Distribution. *Journal of Cognitive Neuroscience*, 11(3), 235-260.
- Bieniek, M. M., Frei, L. S., & Rousselet, G. A. (2013). Early ERPs to faces: aging, luminance, and individual differences. *Frontiers in Psychology*, 4.
- Blomert, L. (2011). The neural signature of orthographic–phonological binding in successful and failing reading development. *Neuroimage*, 57(3), 695-703.
- Brenzitz, Z. (2006). Fluency in reading: Synchronization of processes. *Rocky Mountain Association of Geologists*.
- Calvert, G. A., Spence, C., & Stein, B. E. (2004). *The Handbook of Multisensory Processes*. Mit Press.
- Cappe, C., Thut, G., Romei, V., & Murray, M. M. (2010). Auditory-visual multisensory interactions in humans: timing, topography, directionality, and sources. *Journal of Neuroscience the Official Journal of the Society for Neuroscience*, 30(38), 12572.
- Clayton, F. J., & Hulme, C. (2017). Automatic Activation of Sounds by Letters Occurs Early in Development but is not Impaired in Children With Dyslexia. *Scientific Studies of Reading*(2), 1-15.
- Cohen, L., Dehaene, S., Naccache, L., Lehericy, S., Dehaene-Lambertz, G., & Henaff, M. A., et al. (2000). The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain*, 123(2), 291-307.
- Cornelissen, P. L., Hansen, P. C., Hutton, J. L., Evangelinou, V., & Stein, J. F. (1998). Magnocellular visual function and children's single word reading. *Vision Research*, 38(3), 471-482.
- Cutini, S., Szűcs, D., Mead, N., Huss, M., & Goswami, U. C. (2016). Atypical right hemisphere response to slow temporal modulations in children with developmental dyslexia. *NeuroImage*, 143 40-49. <https://doi.org/10.1016/j.neuroimage.2016.08.012>
- Delorme, A., & Makeig, S. (2003). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, 134(1), 9-21.
- Denckla, M. B., & Rudel, R. G. (1976). Rapid 'automatized' naming (R.A.N.): Dyslexia differentiated from other learning disabilities. *Neuropsychologia*, 14(4), 471-479.
- Facoetti, A., & Molteni, M. (2001). The gradient of visual attention in developmental dyslexia. *Neuropsychologia*, 39(4), 352-357.
- Froyen, D., Atteveldt, N. V., Bonte, M., & Blomert, L. (2008). Cross-modal enhancement of the MMN to speech-sounds indicates early and automatic integration of letters and speech-sounds. *Neuroscience Letters*, 430(1), 23-28.
- Froyen, D., Willems, G., & Blomert, L. (2011). Evidence for a specific cross-modal association

deficit in dyslexia: an electrophysiological study of letter-speech sound processing. *Dev Sci*, 14(4), 635-648.

- Froyen, D. J. W., Bonte, M. L., Nienke, V. A., & Leo, B. (2009). The long road to automation: neurocognitive development of letter-speech sound processing. *Journal of Cognitive Neuroscience*, 21(3), 567-580.
- Froyen, D., Atteveldt, N. V., & Blomert, L. (2010). Exploring the role of low level visual processing in letter-speech sound integration: a visual mmn study. *Frontiers in Integrative Neuroscience*, 4(9), 9.
- Giard, M., Perrin, F. o., Pernier, J., & Bouchet, P. (2010). Brain Generators Implicated in the Processing of Auditory Stimulus Deviance: A Topographic Event-Related Potential Study. *Psychophysiology*, 27(6), 627-640.
- Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, 15(1), 3-10
- Hahn, N., Foxe, J. J., & Molholm, S. (2014). Impairments of multisensory integration and cross-sensory learning as pathways to dyslexia. *Neuroscience & Biobehavioral Reviews*, 47, 384-392.
- Hairston, W. D., Burdette, J. H., Flowers, D. L., Wood, F. B., & Wallace, M. T. (2005). Altered temporal profile of visual-auditory multisensory interactions in dyslexia. *Experimental Brain Research*, 166(3-4), 474-480.
- Hasko, S., Bruder, J., Bartling, J., & Schulte-Körne, G. (2012). N300 indexes deficient integration of orthographic and phonological representations in children with dyslexia. *Neuropsychologia*, 50(5), 640-654. doi:10.1016/j.neuropsychologia.2012.01.001
- Helenius, P., Uutela, K., & Hari, R. (1999). Auditory stream segregation in dyslexic adults. *Brain*(5), 907-913.
- Hillyard, S. A., Teder-Sälejärvi, W. A., & Münte, T. F. (1998). Temporal dynamics of early perceptual processing. *Current Opinion in Neurobiology*, 8(2), 202.
- Howe, A. S. (2014). Meta-analysis of the endogenous N200 latency event-related potential subcomponent in patients with Alzheimer's disease and mild cognitive impairment. *CLINICAL NEUROPHYSIOLOGY -SHANNON-*.
- Institute of Linguistic Studies, Beijing Language and Culture University. (1986). The modern Chinese frequency dictionary. Beijing: Beijing Language and Culture University Press.
- Jaskowski, P., & Rusiak, P. (2008). Temporal order judgment in dyslexia. *Psychological Research*, 72(1), 65-73.
- Laasonen, M., Service, E., & Virsu, V. (2002). Crossmodal Temporal Order and Processing Acuity in Developmentally Dyslexic Young Adults. *Brain & Language*, 80(3), 340-354.
- Li, D., Chen, G. P., & Jin, Y. (1989). Combined Raven's matrices test (Revised ed.). Shanghai: East China Normal University Press.
- Livingstone, M.S., Rosen, G.D., Drislane, F.W., & Galaburda, A.M. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proceedings of the National Academy of Sciences*. 88(18), 7943-7947
- Lovegrove, W., Slaghuys, W., Bowling, A., Nelson, P., & Geeves, E. (1986). Spatial frequency processing and the prediction of reading ability: A preliminary investigation. *Perception & Psychophysics*, 40(6), 440-444.
- Lyon, G. R., Shaywitz, S.E. & Shaywitz, B.A. (2003). A definition of dyslexia. *Ann. of Dyslexia*, 53(1), 1-14.
- Male, A. G., & Gouldthorp, B. (2020). Hemispheric differences in perceptual integration during language comprehension: An ERP study. *Neuropsychologia*, 139, 107353-.
- Meilleur, A., Foster, N. E. V., Coll, S. M., Brambati, S. M., & Hyde, K. L. (2020). Unisensory and multisensory temporal processing in autism and dyslexia: A systematic review and meta-analysis. *Neuroscience & Biobehavioral Reviews*, 116.
- Meng, X., Cheng-Lai, A., Zeng, B., Stein, J. F., & Zhou, X. (2011). Dynamic visual perception and reading development in Chinese school children. *Annals of Dyslexia*, 61(2), 161-176.
- Mercier, M. R., & Cappe, C. (2020). The interplay between multisensory integration and perceptual decision making. *Neuroimage*, 222, 116970.
- Mittag, M., Takegata, R., & Kujala, T. (2011). The effects of visual material and temporal synchrony on the processing of letters and speech sounds. *Experimental Brain Research*, 211(2), 287-298.

- Mittag, M., Thesleff, P., Laasonen, M., & Kujala, T. (2013). The neurophysiological basis of the integration of written and heard syllables in dyslexic adults. *Clinical Neurophysiology*, 124, 315–326.
- Nash, H. M., Gooch, D., Hulme, C., Mahajan, Y., McArthur, G., Steinmetzger, K., & Snowling, M. J. (2016). Are the literacy difficulties that characterize developmental dyslexia associated with a failure to integrate letters and speech sounds? *Developmental Science*, 20(4).
- Penolazzi, B., Spironelli, C., Vio, C., & Angrilli, A. (2006). Altered hemispheric asymmetry during word processing in dyslexic children: An event-related potential study. *Neuroreport*, 17(4), 429–433.
- Polich, J. (2007). Updating P300: an integrative theory of P3a and P3b. *Clinical Neurophysiology*, 118(10), 2128–2148.
- Ponton, C. W., Eggermont, J. J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: evidence from multi-channel evoked potentials. *Clinical Neurophysiology*, 111(2), 220–236.
- Qian, Y., & Bi, H. Y. (2015). The effect of magnocellular-based visual-motor intervention on Chinese children with developmental dyslexia. *Frontiers in Psychology*, 6, 1529.
- Qian, Y., Deng, Y., Zhao, J., & Bi, H. Y. (2015). Magnocellular-dorsal pathway function is associated with orthographic but not phonological skill: fMRI evidence from skilled Chinese readers. *Neuropsychologia*, 71, 84–90.
- Sams. (1983). Sequential effects on the ERP in discriminating two stimuli. *Biological Psychology*, 17(1), 41–58.
- Sehyr, Z. S., Midgley, K. J., Holcomb, P. J., Emmorey, K., & Behrmann, M. (2020). Unique N170 signatures to words and faces in deaf ASL signers reflect experience-specific adaptations during early visual processing. *Neuropsychologia*, 141, 107414.
- Schneider, W., Eschman, A., & Zuccolotto, A. (2002). E-Prime Reference Guide. Psychology Software Tools.
- Schröger, E. (1998). Measurement and interpretation of the mismatch negativity. *Behavior Research Methods, Instruments, & Computers*, 30(1), 131–145.
- Shaul, S. (2014). Visual, auditory and cross modal lexical decision: a comparison between dyslexic and typical readers. *Psychology*, 05(16), 1855–1869.
- Shu, H., McBride-Chang, C., Wu, S., & Liu, H. (2006). Understanding Chinese developmental dyslexia: Morphological awareness as a core cognitive construct. *Journal of Educational Psychology*, 98(1).
- Spironelli, C., & Angrilli, A. (2007). Influence of Phonological, Semantic and Orthographic tasks on the early linguistic components N150 and N350. *International Journal of Psychophysiology Official Journal of the International Organization of Psychophysiology*, 64(2), 190–198.
- Takeshi, H., Kazuhito, Y., Yasuhiro, I., Mitsuhiro, M., & Hidehiro, K. (2013). Reliability and validity of the digit cancellation test, a brief screen of attention. *Psychologia*, 55(4), 246–256.
- Tatiana, S., Clément, F. O., Daniele, S. N., Alexandra, C., Fabien, P., Barbara, T., & Troyer, T. W. (2014). Metrical Presentation Boosts Implicit Learning of Artificial Grammar. *Plos One*, 9(11), e112233.
- Tijms, J., & Hoeks, J. (2010). A computerized treatment of dyslexia: Benefits from treating lexico-phonological processing problems. *Dyslexia*, 11(1).
- Van Atteveldt, N.M., Formisano, E., Blomert, L., & Goebel, R. (2007). The Effect of Temporal Asynchrony on the Multisensory Integration of Letters and Speech Sounds. *Cerebral Cortex*, 17(4), 962–974.
- Virsu, V., Lahti-Nuuttila, P., & Laasonen, M. (2003). Crossmodal temporal processing acuity impairment aggravates with age in developmental dyslexia. *Neuroscience Letters*, 336(3), 151–154.
- Wallace, M. T., & Stevenson, R. A. (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia*, 64, 105–123.
- Wang, J. J., Bi, H. Y., Gao, L. Q., & Wydell, T. N. (2010). The visual magnocellular pathway in Chinesespeaking children with developmental dyslexia. *Neuropsychologia*, 48, 3627–3633.
- Wang, X., & Tao, B. (1996). Chinese character recognition test battery and assessment scale for primary school children. Shanghai: Shanghai Education Press.
- Wimmer, H., & Schurz, M. (2010). Dyslexia in regular orthographies: manifestation and

causation. *Dyslexia*, 16(4), 283-299.

Žarić, G., González, G.F., Tijms, J., van der Molen, M.W., Blomert, L., & Bonte, M. (2014). Reduced neural integration of letters and speech sounds in dyslexic children scales with individual differences in reading fluency. *PLoS ONE*, 9 (10), e110337.

Table 1. Mean (SD) age and scores on reading-related skills in developmental dyslexia (DD) and typically developing (TD) groups

	TD group (n=14) M (SD)	DD group(n=13) M(SD)	T value
Gender(male/female)	10/4	10/3	
Age(years)	10.19(0.69)	10.19(0.66)	0.01
CRT [†]	114.85(11.31)	106.92(11.16)	1.8
CCRT [‡]	2708.69(380.69)	1917.34(530.00)	4.378***
Reading fluency	93.38(16.19)	77.38(16.59)	2.49*
Reading accuracy	98.69(10.60)	87.31(9.38)	2.90**
Morphological awareness	16.08 (2.10)	14.00(1.87)	2.66*
Phonological awareness	28.23 (1.74)	23.92(3.55)	3.93*
Rapid naming	15.31(2.09)	17.88(2.62)	-1.76
Short memory	6.64(0.94)	6.15(1.44)	-0.293
Visual spatial attention	31.67(5.52)	27.23(6.43)	-1.844

[†]CRT combined Raven's test

[‡]CCRT Chinese character recognition test

*p<0.05, **p<0.01, ***p<0.001

Table 2 Mean number of epochs in the baseline and congruent conditions in each group and each SOA

	Conditions	AV0 M(SD)	AV300 M(SD)	AV600 M(SD)
TD (N = 14)	Baseline	60.46(12.39)	56.69(14.42)	52(17.68)
	Congruent	62.85(11.10)	57.15(13.52)	52(16.41)
DD (N = 13)	Baseline	67.08(10.56)	62.23(11.77)	59.15(13.56)
	Congruent	66.62(11.86)	62.38(11.94)	58.69(14.51)

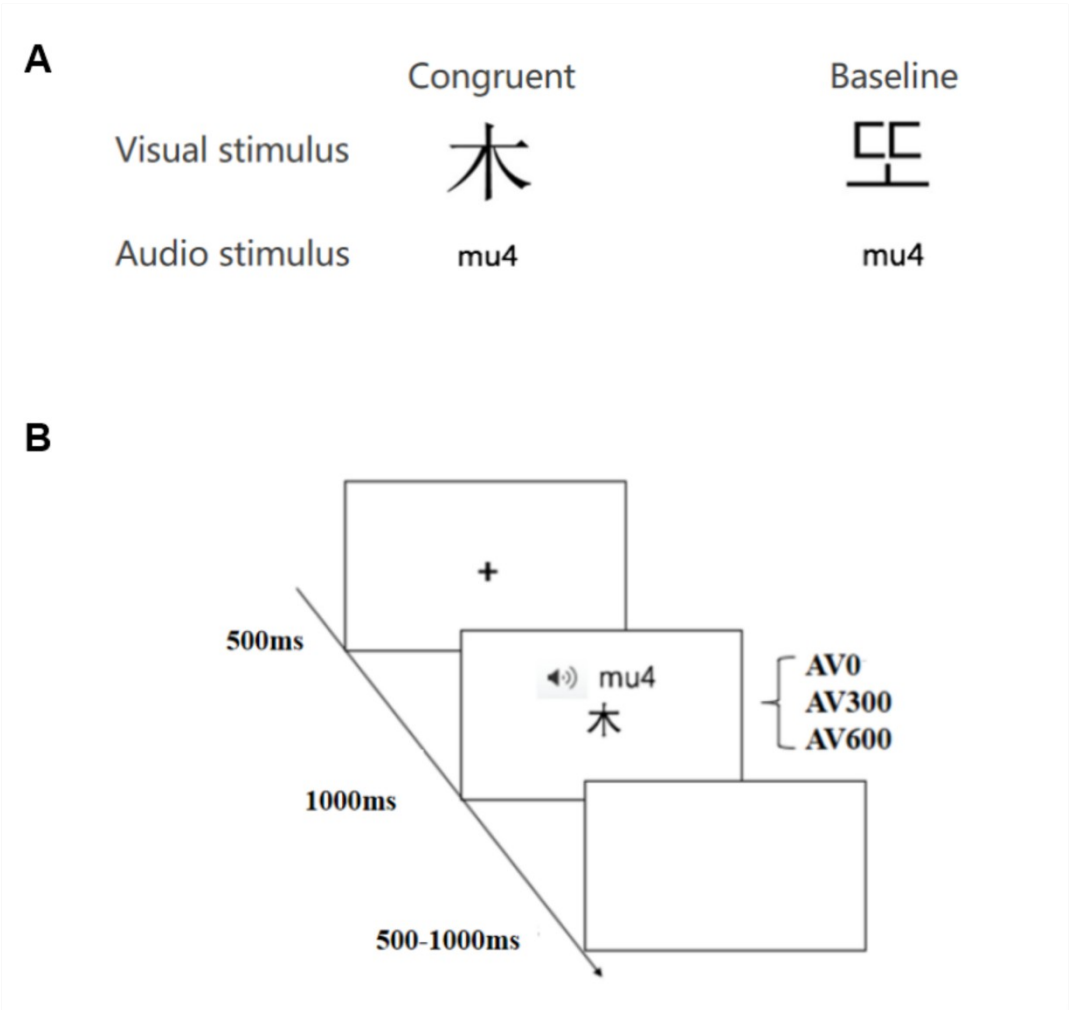


Figure 1. Schematic description of the experimental design. (A) Shows an example of cross-modal stimuli pairs in congruent and baseline conditions. Visual stimuli were either written Chinese characters or Korean symbols. Auditory stimuli were pronunciations of a Chinese character. (B) Illustrates the stimulus sequences within an experimental trial. Each trial starts with a central fixation presenting for 500 ms,

followed by a visual stimulus with the duration of 1000 ms. Auditory stimulus was presented synchronously or after a 300 ms or 600 ms time interval. The visual stimulus was followed by a random blank interval of 500-1000 ms.

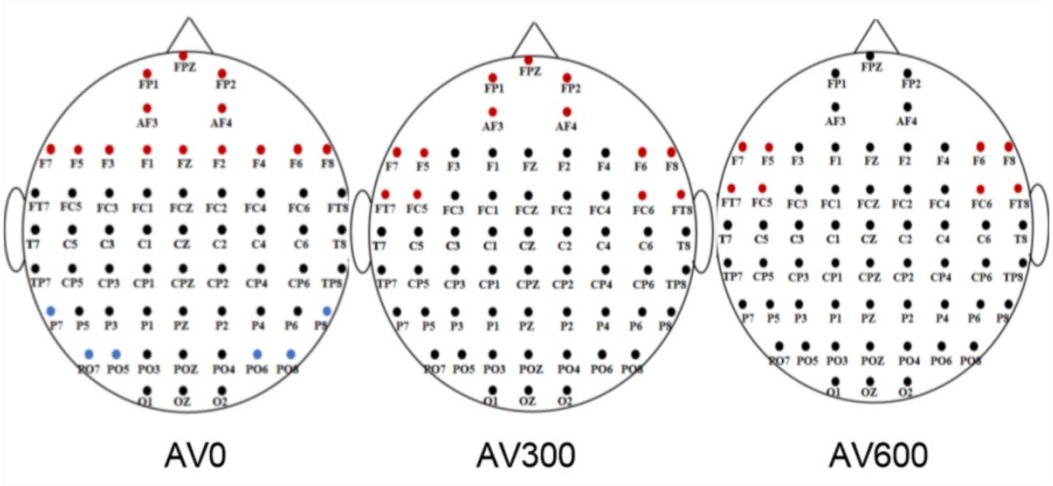


Figure 2. The layout of the configuration of electrodes and selection of electrodes for data analysis. In the AV0 condition, the electrodes marked by blue dots are selected for the analysis of P1 and N170. The electrodes marked by red dots are selected for the analysis of N300. In the AV300 and AV600 condition, the electrodes marked by red dots are selected for the analysis of N200.

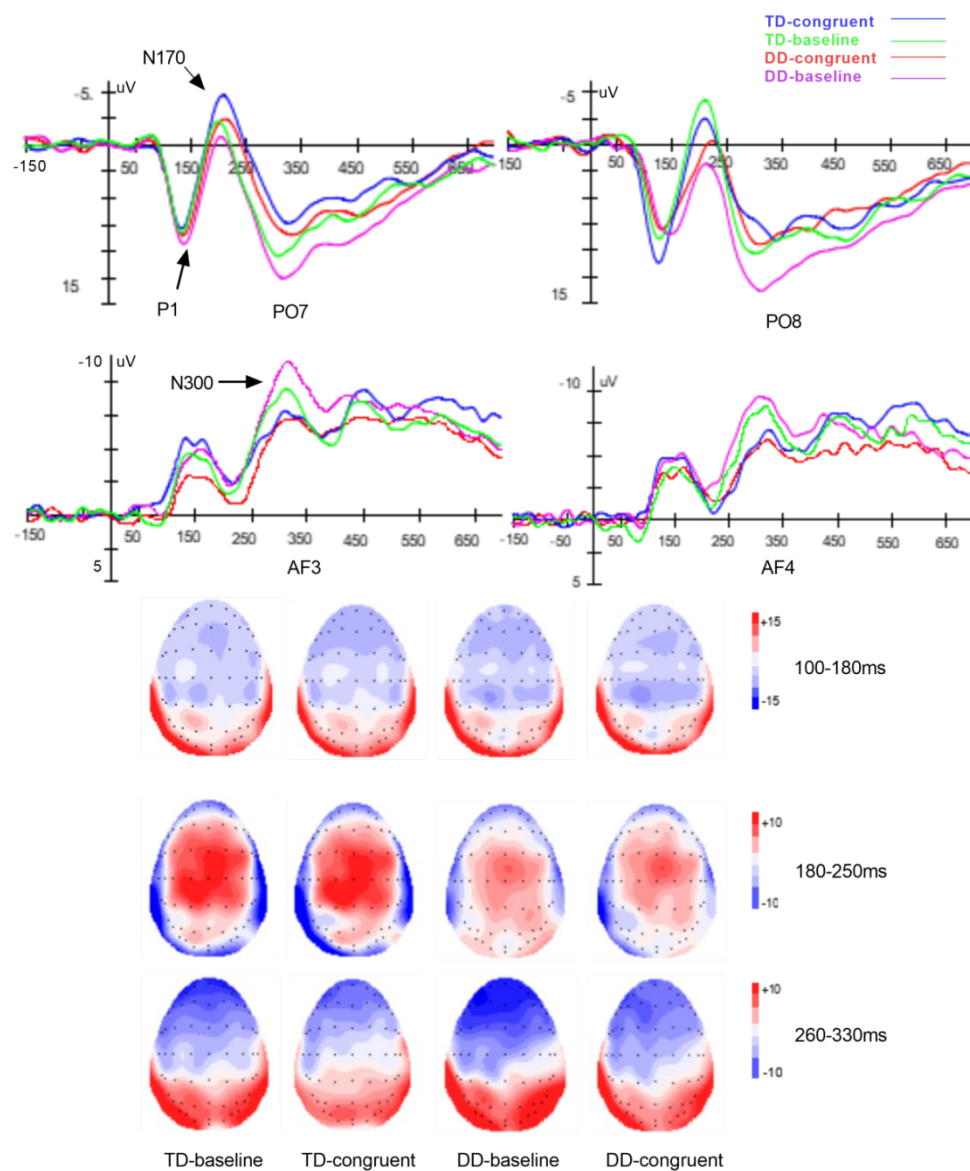


Figure 3. Grand average ERPs and topographic graphs in response to the auditory onset under the AV0 condition. Multisensory integrations were involved in the time windows of 110-180 ms, 180-250 ms, and 260-340 ms. The early P1 and N170 can be observed on PO7/8 electrodes, and fronto-temporal N300 can be observed on the AF3/4 electrodes.

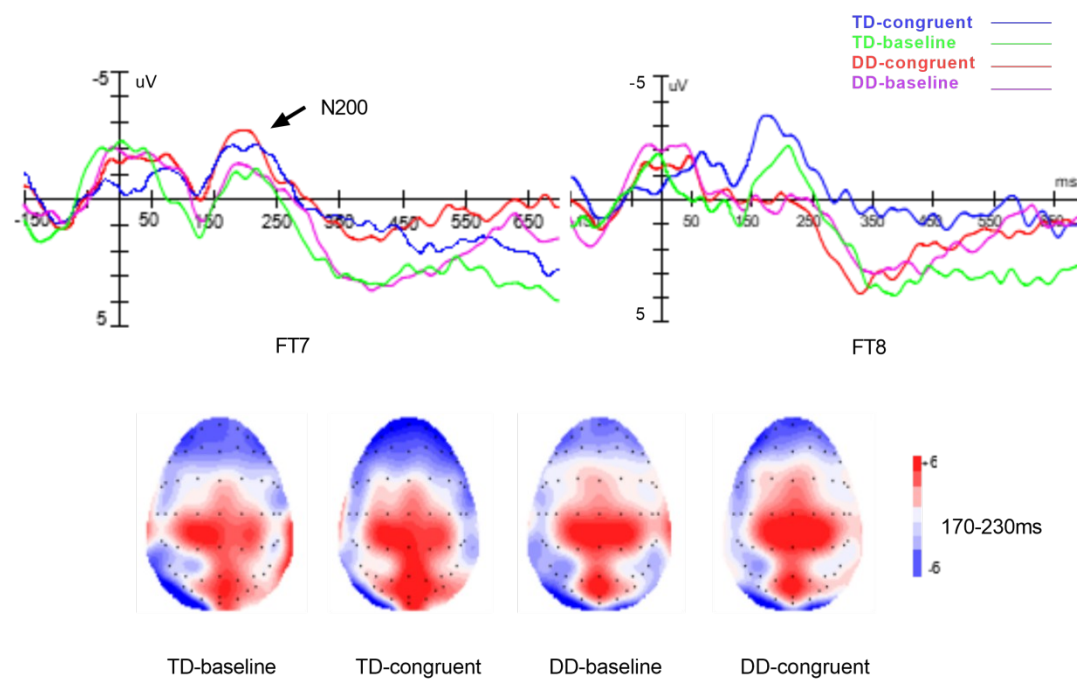


Figure 4. Grand average ERPs and topographic graphs in response to the auditory onset under the AV300 condition. Multisensory integrations were involved in the time windows of 170-230 ms.

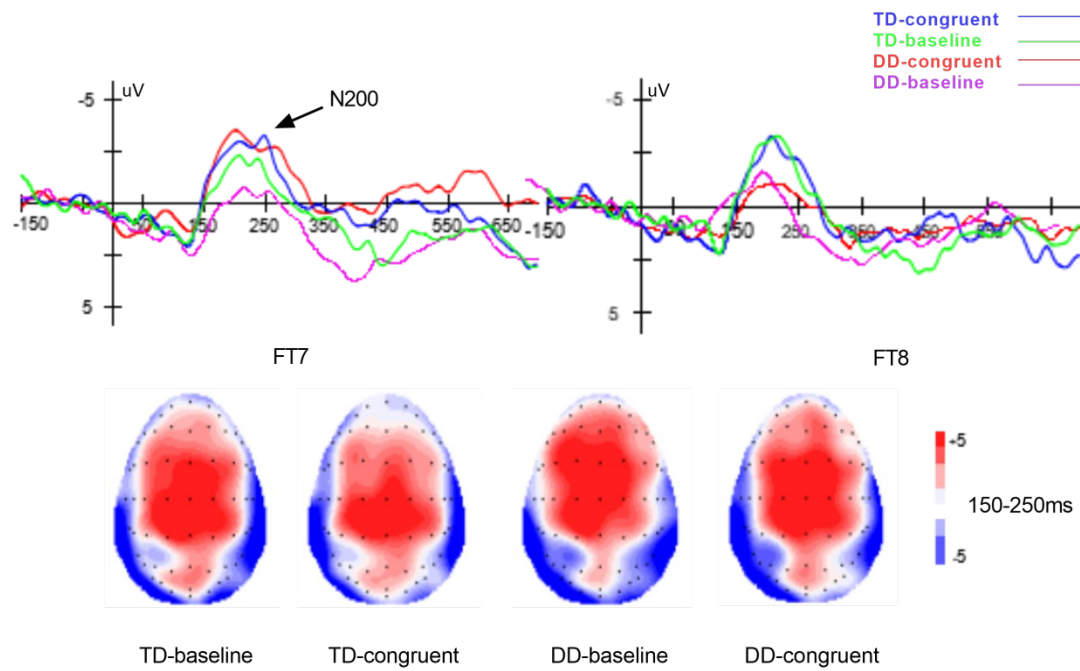


Figure 5. Grand average ERPs and topographic graphs in response to the auditory onset under the AV600 condition. Multisensory integrations were involved in the time windows of 150-250 ms.